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An Optical Control System for Millimeter Wave Phased-Array Antennas

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ABSTRACT

Novel compact electrooptic control systems are introduced for microwave and millimeter wave phased array antennas that use dual-laser frequency heterodyning techniques for radio frequency (rf) signal generation, and nematic liquid crystals for rf phase and amplitude control.

2. INTRODUCTION

The proposed phased array control systems are based on mature optoelectronic technologies such as nematic liquid crystal displays, acousto-optics, tunable single frequency lasers, high speed photodiodes, bulk optics, and fiber-optics. These optoelectronic systems use single frequency lasers for signal generation required for both transmit and receive mode two dimensional antenna beam steering. The electrooptic controllers can be compact and light-weight. Applications include satellite communication phased arrays, ground-based communication terminals, and high resolution airborne radars.

In particular, a unique, carrier tunable, optical system is introduced for controlling millimeter wave phased array antennas. The system uses dual-frequency laser heterodyning, nematic liquid crystals, and millimeter wave monolithic integrated circuit modules to provide signal parameter and carrier control in an analog fashion. These optoelectronic controllers use the interference of two optical beams having a relative optical frequency shift to generate the microwave/millimeter wave antenna control signals. Heterodyne detection of the two optical beams at a photodiode generates the desired electrical carrier. The photodiode acts as an optical mixer, allowing only the lower difference frequency term to pass as an electrical output. Fundamental to the carrier frequency generation via optical heterodyning is the use of an optical interferometer. Microwave/millimeter wave frequency generation is achieved using the interference of two color shifted optical beams available from single frequency tunable lasers such as the diode-pumped non-planar ring lasers. For narrow line widths of less than a 5 KHz for the optically generated carrier, the tunable lasers have to be externally phase-locked, and thermal and piezoelectric tuning is used for color shifting the lasers. Carrier modulation (both amplitude and frequency) can be achieved in various ways such as through Bragg cells (frequency shifters) positioned in the color shifted beams that form the interferometer, or through external integrated-optic electro-optic amplitude modulators.

3. RF BEAT SIGNAL GENERATION METHODS

Fig.1 shows the basic optical beamformer system diagram. A key sub-system of the control system is the rf beat signal generation optical system. There are various ways in which the beat

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signal can be generated, each having its features and limitations. Fig.2 shows the acoustooptic (AO) technique that is based on the in-line AO interferometer. This system has been demonstrated and is described in several papers by N. A. Riza [1-4]. The AO interferometer technique generates high quality rf signals over both short (< 1 ms) and long durations (e.g., 100 ms). The in-line, almost common-path, single laser interferometric design makes the output rf signal (and its phase noise) essentially independent of the laser phase noise. Thus, a high quality rf signal fed to the Bragg cells in the AO system can generate high quality carrier signals for the antenna array. Nevertheless, this approach is limited in optical efficiency (e.g., 20 % with rf AODs) and maximum frequency range (e.g., 8 GHz when using wideband cells); although rf cells with frequency up-conversion using mixing alleviates the frequency range problem.

Fig.3 shows another approach to optical beat signal generation. This is the well-known single sideband quadrature phase shift method some times used in electronic communications [5]. Here, 90 degree rf and optical phase shifters and 1:1 optical and rf combiners/splitters are used to form a network structure that results in generating two optical beams with the required single sideband frequency shift. Although this approach can result in a compact, robust sub-system by virtue of using integrated optics, it too has certain limitations. This approach is extremely sensitive to rf and optical amplitude and phase variations, and exact amplitude and phase levels are required for good single sideband suppression for high quality signal generation.

Fig.4 shows the third method for beat frequency signal generation that uses optical mixing of two highly stable color shifted lasers. This approach has a very high optical efficiency, and is tunable over very wide microwave and millimeter wave bandwidths. Various researchers have shown rf signal generation by this method. DC-50 GHz tunable rf signals have been generated by this method without active external laser stablization [6]. Using low noise diode-laser pumped Nd: YAG ring lasers without locking, < 5 KHz linewidth rf signals have been demonstrated over short millisecond durations. Using some what complex external optical/electronic phase locking methods, narrower linewidths up to 193 mHz have been demonstrated using these low noise diode-laser pumped Nd: YAG ring lasers [7-9]. In fact, recently, researchers at Lightwave Electronics Corp. have generated open-loop signals up to 117 GHz, and phase locked signals up to 20 GHz [10]. Semiconductor lasers have also been used to generate microwave and millimeter wave signals [11]. Because of the rapidly maturing optoelectronic hardware for two laser beat frequency signal generation, this paper describes how nematic liquid crystals can be combined with the dual-laser system to control phased array antennas.

4. PHASED ARRAY OPTICAL CONTROLLERS

Fig.5 shows the basic dual-laser interferometer-based optical beamformer for phased arrays. Appropriate beam expansion bulk optics is used to illuminate a pair of two dimensional nematic liquid crystal devices that have been pixelated. These electrically controlled parallel-rub birefringent mode nematic liquid crystals provide optical phase modulation that can be translated to electrical or carrier phase and amplitude modulation at the photodiode output. Because nematic liquid crystals rotate in an analog fashion, the signal control provided by the optoelectronic controller is also analog, as recently demonstrated in earlier experiments [4]. This can lead to very low antenna sidelobes and system calibration capabilities. This element level antenna control feature of the proposed optical beamformer is critical in practical antenna systems that have element level amplitude and phase errors that need to be cancelled out. Both rf signal generation and control is done in the optical domain, thus greatly reducing the EMI and control accuracy problems associated with millimeter wave MMIC phase shifters, splitters, combiners, and amplitude trimmers. The optical controller in Fig.5 is compact (30 cm by 20 cm) and weighs a few pounds. The controller consumes very little (mWs) control power as low power nematic liquid crystal devices perform the array amplitude and phase control functions. The system has a widely tunable carrier, and its free-space design can be readily adapted to provide control and generation capability of multiple, simultaneous, phased array beams, such as those needed in communication applications. The switching speed of nematic liquid crystals is limited (e.g., 1 ms), and some applications such as tracking radar require fast 1000 beams/s antenna scan rates. This problem can be solved using a two channel time multiplexed beam scanning approach using a two channel system as shown in Fig.6. In this case, while channel 1 is active for antenna operation, channel 2 is resetting for the next antenna beam position, and vice versa. Because typical radar dwell times are in milliseconds, there is enough time for the nematic liquid crystals to reset. In addition, the use of independent, simultaneous, multiple beams reduces the antenna scan rate requirement, and thus the speed limitation of nematic liquid crystals can further be alleviated.

The controllers in Fig.5 and Fig.6 generate a set of rf signals at the desired antenna carrier that also have the correct phase and amplitude values required for antenna beam steering for the transmit mode. Thus, the system is ideal for transmit phased arrays used in satcom type terminals. The optical controller can also be used in receive arrays, although, in this case, a microwave/millimeter wave mixer is required at each antenna element, and the received signals are summed in an IF combiner (see Fig.7). Thus, the optical controller can be used for a transmit-receive mode antenna such as in radar and seeker applications, although at the added complexity of requiring an array of microwave/millimeter wave mixers, a not so trivial task.

5. CONCLUSION

We have described novel optical controllers for phased arrays that operate over a wide tunable microwave/millimeter wave band. The system is ideal for transmit phased arrays in the millimeter wave band where EMI and millimeter wave monolithic integrated circuit devices (phase shifters, trimmers, splitters, etc) performance limitations become apparent, and thus restrict the true ability of the phased array antenna. Future work will describe experimental results.

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THE OPTICAL BEAMFORMER SYSTEM DIAGRAM

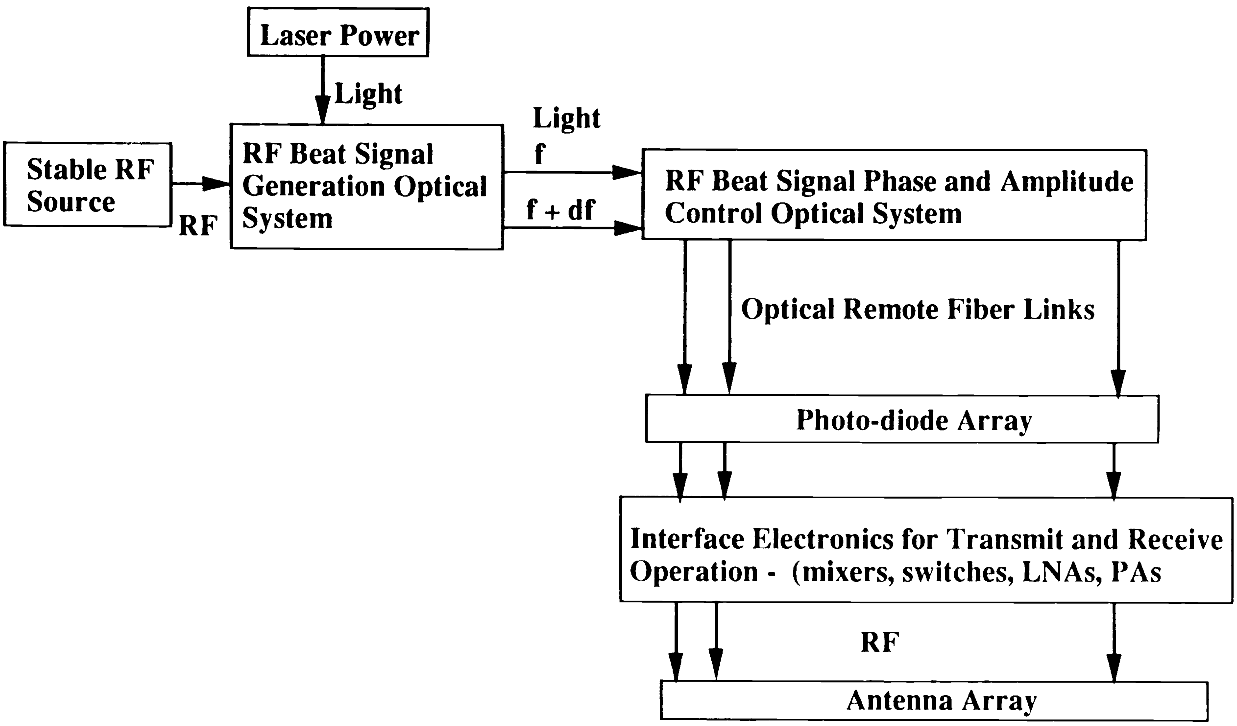

Fig.1 The basic optical beamformer system diagram.

The In-line AO Interferometer

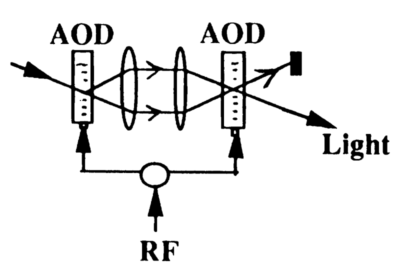

Fig.2 The acoustooptic (AO) technique that is based on the in-line AO interferometer.

Single-Sideband

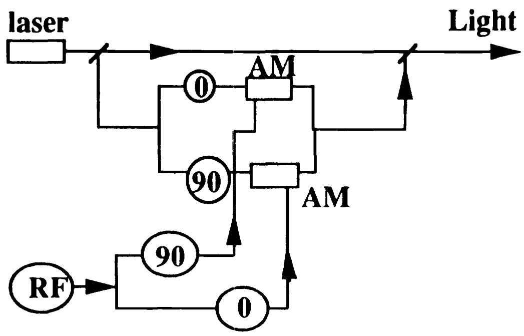

Fig.3 The single sideband quadrature phase shift method approach to optical beat signal generation.

2-Laser Mixing

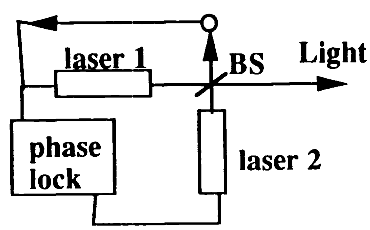

Fig.4 The beat frequency signal generation method that uses optical mixing of two highly stable color shifted lasers.

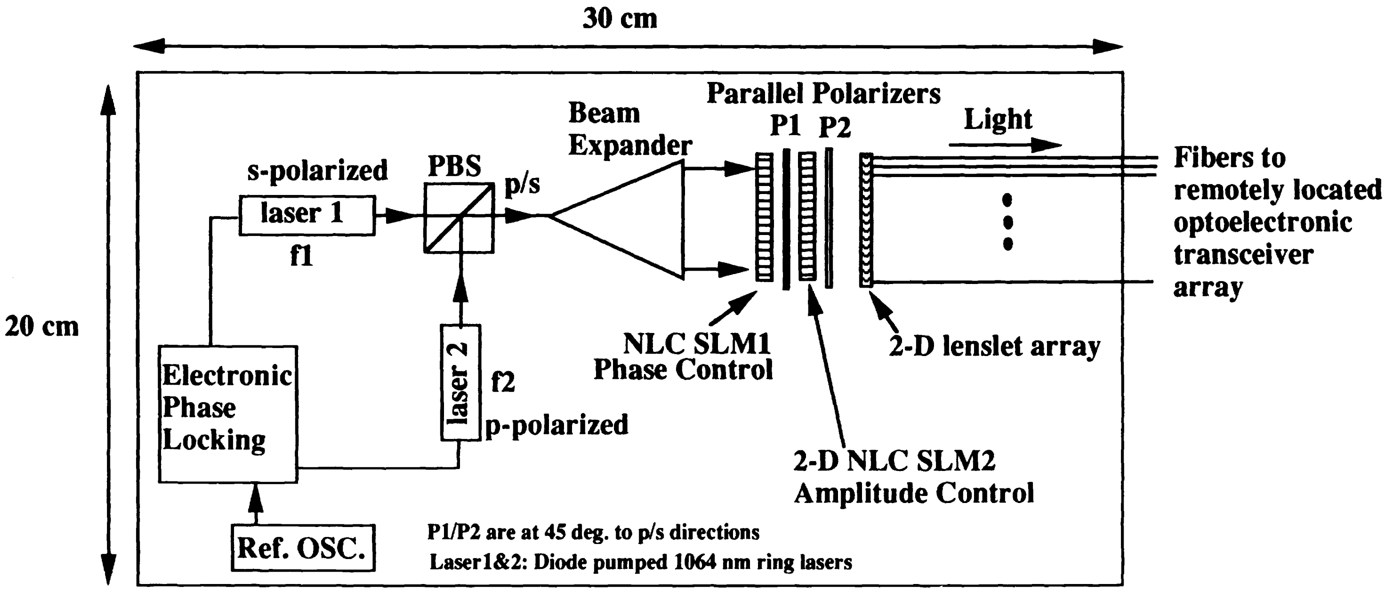

Fig.5 The basic dual-laser interferometer-based optical beamformer for phased arrays that uses nematic liquid crystals arrays for antenna array signal amplitude and phase control.

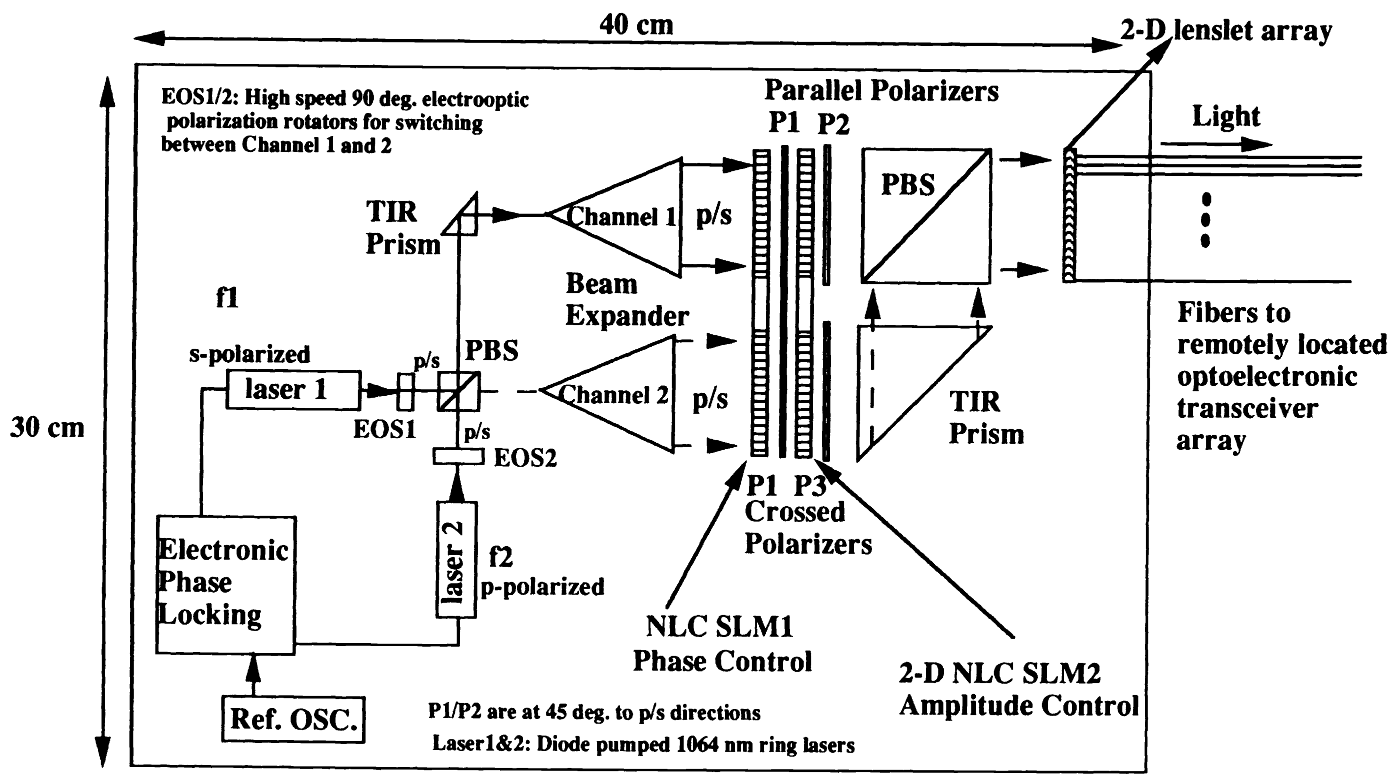

Fig.6 A two channel time multiplexed beam scanning approach using a two channel system for optical control of phased arrays. In this case, while channel 1 is active for antenna operation, channel 2 is resetting for the next antenna beam position, and vice versa.

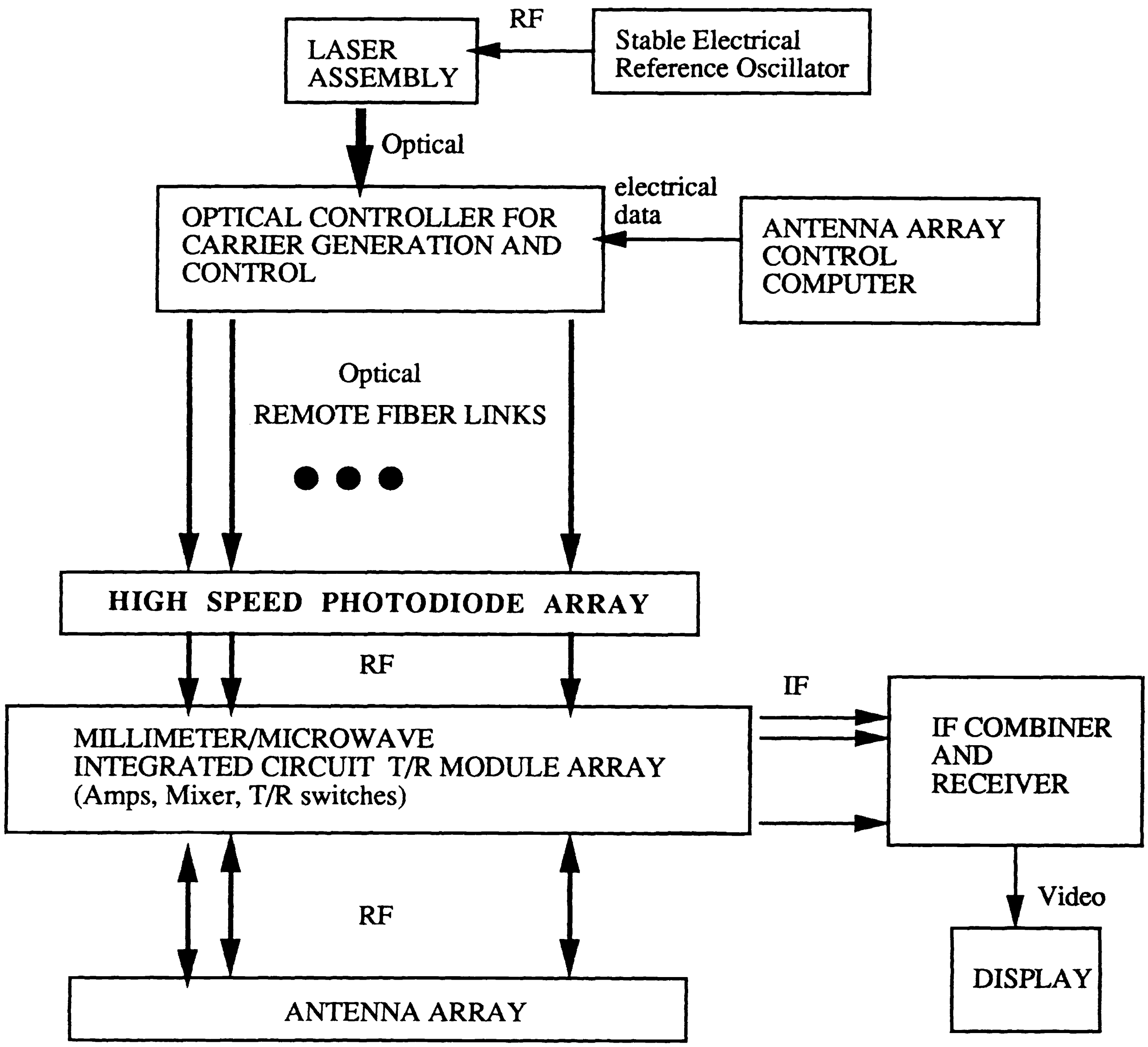

Fig.7 The optical controller system diagram when used for both transmit and receive antenna operation such as in radar.